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LONG RANGE PROPAGATION OF SPHERICAL SHOCKWAVES FROM EXPLOSIONS IN AIR

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22 JULY 1969

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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ABSTRACT: Hydrocode calculations for spherical shock propagation using the artificial-viscosity method are carried out to 0.2 psi overpressure for a nuclear explosion and for a TNT explosion. An ideal-gas integration from the literature is used to extend the results to 1.6×10^{-4} psi. Below 1.0 psi, 1 kt nuclear is equivalent to 0.7 kilotons of TNT.

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Although there has been occasional interest in using analytical techniques to predict explosion shockwave pressures out to large distances, there has been little emphasis on employing modern computer techniques to provide such predictions. Use of nuclear explosions for peaceful purposes--such as digging a canal--requires accurate evaluation of possible airblast damage among other considerations. A necessary part of the airblast evaluation is an accurate free-air pressure-distance curve for explosions. This report presents results obtained toward that end for both nuclear and for TNT explosions.

This investigation was sponsored jointly by the Defense Atomic Support Agency (under RIN 1004, Work Unit 1027) and by the Atlantic-Pacific Interoceanic Canal Feasibility Studies Program (Nuclear Safety Program--Acoustic Wave Effects Project).

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Captain, USN
Commander

C. J. Aronson

C. J. ARONSON
By direction

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1. INTRODUCTION

In the past, most hydrocode calculations for explosions in real air were stopped at shock overpressures near 1.0 psi either because of numerical difficulties or because of lack of interest in such low pressures. In this report we discuss calculations that we have carried out to about 0.2 psi.

We are concerned here only with sea-level, free-air explosions; i.e., explosions that occur in an infinite volume of air at one atmosphere pressure and 15°C. Results for this uniform-atmosphere situation are of interest because they can be used as base data for calculations including atmospheric perturbations.

2. THE PRESENT CALCULATIONS

2.1 Nuclear Explosion

A homogeneous-sphere model is used for the explosion. The initial condition is a quiescent sphere of heated real air 4.251 meters in radius, at ambient density (0.001225 g/cm^3) and containing 1KT (10^{12} calories) of internal energy. The solution to this initial-value problem is generated by the WUNDY hydrocode (ref. 1), with changes to the rezoning routine, a more accurate equation of state for air, and double precision in critical quantities. A zone size of two meters was used in the shock wave. To prevent excessive rounding of the shock front, the linear viscosity was decreased as the shock became weaker.

The calculated overpressure vs distance data are given in columns 1 and 4 of Table I and in Figure 1. (The calculations were stopped at 0.2 psi because of high computer cost.) These data are in satisfactory agreement with nuclear test data over the range 10^4 to 7 psi as shown on Figure 1 of ref. 2a for earlier WUNDY calculations. Below 10 psi the present calculations are found to agree with the aircraft curve of Figure 3.3-7 of ref. 2b. Figure 1 also shows the lower end of the theoretical Problem M curve (ref. 3).

2.2 TNT Explosion

A similar calculation was made for a one-pound sphere of TNT. The conditions inside the charge at the time the detonation wave reaches the surface were calculated from the spherical Taylor wave with the LSZK equation of state for the explosion products (ref. 4). These calculations are similar to those reported in reference 5 except that a more recent equation of state for air was used and the calculation was carried much further (ref. 5 stopped at 2.5 psi). A zone size of one cm was used in the shock wave.

The calculated overpressure vs distance data are given in columns 1 and 5 of Table I and in Figure 2.

3. EXTENSION OF PRESENT CALCULATIONS

3.1 Soviet Calculations

The problem of a nuclear explosion in ideal air (gamma=1.4) has been calculated by Brode (ref. 6), by Goldstine and von Neumann (ref. 7), and by Okhotsimskii, et al (ref. 8). All of these calculations stop near 1.0 psi. Brode used the artificial viscosity method. References 7 and 8 used shock fitting. All of these solutions are in excellent agreement. We also calculated this problem with WUNDY to about 1.0 psi to verify our method of calculation and found excellent agreement with these previous solutions.

The ideal air situation is of interest here because the calculation of reference 8 was extended by Okhotsimskii and Vlasova (ref. 9) to a very large distance (to 0.00016 psi). They continued to use shock fitting but rewrote the difference equations for the flow behind the front in terms of overpressure, overdensity, etc. to avoid numerical difficulties. (We did the equivalent thing by using double precision in our calculations.) The solution in reference 9 was carried to 0.03 psi, where it was stopped by numerical instabilities. It was carried further by an approximate method of Khristianovich. The net result was a numerical solution out to 0.00016 psi. The numerical values for overpressure vs radius are given in columns 1, 2 and 3 of Table I. The logarithmic slope of the pressure vs distance curve is shown in Figure 3. The slope has the point source value of -3.0 near the explosion and gradually approaches -1.0 at low pressures. Figure 3 also shows the slope for the present real-air calculations.

We will use this Okhotsimskii-Vlasova solution for ideal air to extend our present calculations for real air.

3.2 Asymptotic Behavior

The problem of propagation of a spherical shockwave to very large distances has been considered by Kirkwood and Bethe (ref. 10), by Landau (see ref. 11), and by Whitham (ref. 12), all of whom arrived at the following asymptotic formula for decay of peak overpressure:

$$\Delta P = A\left[br \sqrt{\ln(br)} \right]^{-1} \qquad (1)$$

where ΔP is peak shock front overpressure, r is radial distance from the origin to the shock front, and A and b are constants. This equation arises from an argument based on the logarithmic divergence of the characteristics behind the shock front. Equation (1) has been used by Miles (ref. 13) to extend the numerical calculations of Brode (ref. 14) to very low pressures.

This equation is consistent with the Okhotsimskii-Vlasova solution; we were able to fit their calculated results within one percent for the range below 0.4 psi.

We have not used this equation in the results we give in this report. It has been used here only as a check on the asymptotic behavior of the Soviet calculation.

4. EFFECTIVE BLAST YIELDS

Each of these calculations obeys yield scaling exactly; i.e., the radius at which a given overpressure occurs is proportional to the cube root of the explosion energy. However, the three different types of explosions considered here (nuclear in ideal air, nuclear in real air, and TNT in real air) all give different amounts of dissipation near the source and thus have different amounts of energy available for the far-out blast wave.

We can compare the "effective blast yields" of two explosions by simply noting the distances at which a given overpressure occurs. The farther an explosion is able to give a given overpressure, the greater its effective yield. The effective yield ratio (at a given overpressure) of two explosions is simply the cube of the distance ratio. Figure 4 shows the effective blast yield of the calculated 1KT nuclear explosion vs to calculated one pound TNT explosion scaled to two million pounds, both in real air. The line is drawn by eye through the calculated points. The effective yield varies with overpressure, as expected, since the pressure-vs-distance curves are not parallel. The effective yield appears to settle down near 0.7 below 1.0 psi*. This gives an energy equivalence, for explosions in real air:

0.7 kilotons TNT = 1.0KT nuclear (below 1.0 psi).

In a similar way, the ideal nuclear explosion can be compared with the real-air nuclear explosion. Figure 5 shows the effective yield. The energy equivalence at low pressures is:

0.71KT nuclear, ideal air = 1.0KT nuclear, real air (below 7.0 psi).

Figure 5 also shows the energy equivalence for the Problem M calculation (ref. 3). Problem M takes an upward turn near 2.0 psi.

If we assume that these effective yields remain constant (i.e., that the overpressure vs distance curves remain parallel) for all overpressures below 0.2 psi, we can extend the real-air calculations by using the ideal-air results with the appropriate effective yield. To get the nuclear real-air distances, we multiply the ideal-air distances by $(0.71)^{1/3} = 0.892$. To get the distances in meters for one pound of TNT, we multiply the ideal-air distances by 7.98. (To get the distances for 1 kiloton of TNT, we multiply the ideal-air distances by $(0.71/0.70)^{1/3} = 1.005$.) The "extended" pressure vs distance data are shown in columns 4 and 5 of Table I beginning at 0.1927 psi and are marked by asterisks.

*The well-known value of 0.5 in the 5-50 psi range comes from TNT data that lie about 15 per cent above the curve of Figure 2.

5. COMPARISONS WITH EXPERIMENT

The agreement of the nuclear real-air calculation with experimental free-air data (not shown here) is satisfactory in the 0.1-100 psi region.

For high explosives, the only available free-air data below 0.1 psi are from Project BANSHEE. The BANSHEE events were 500-lb pentolite (not TNT) spheres detonated at altitudes up to 103,000 feet. Microbarograph measurements were made at the ground by Sandia and by BRL. The Sandia data (ref. 15) are shown on Figure 2. The slant range divided by $(500)^{1/3} = 7.94$ is plotted against measured reflected overpressure divided by two to convert it to incident overpressure. These events took place in non-sea level ambient conditions. The use of slant range versus overpressure corresponds to assuming that modified Sachs scaling holds (ref. 16).

The BANSHEE data are quite near the theoretical curve (Fig. 2).

Some surface-burst data are available in the 0.003-1 psi range. It is not necessarily appropriate to compare free-air pressures with surface-burst pressures measured near the surface. However, two sets of surface burst data are shown for comparison in Figure 2.

<u>BRL surface burst data</u>: These data are pressure-gage measurements (ref. 17) from 5, 20, and 100 ton surface bursts in Canada in 1959-61. The charges were formed of TNT blocks stacked on the ground to form a hemisphere. The plotted distances have been divided by $(2\ W)^{1/3}$ to reduce them to one pound in free air. (The factor of 2 used here is for a rigid surface and does not allow for close-in energy losses to the ground. This number may be as low as 1.5, depending on which free-air data are used in obtaining it. The exact value does not matter for our purposes.)

<u>NOL micro-ton surface burst data</u>: The dashed line on Figure 2 is a fit to 145 pressure-gage measurements (ref. 18) from surface-burst #6 electric blasting caps having an equivalent yield of 0.44 grams TNT:

$$\Delta p = 8.21\ R^{-1.42}$$

where Δp is overpressure in psi and R is radius in feet. The plotted distances have been divided by $(2\ W)^{1/3}$ to reduce them to one pound in free air.

The surface-burst data agree quite well with the calculated free-air curve down to about 0.2 psi. Below 0.2 psi the surface-burst data have a much faster rate of decay of pressure with distance than does the free-air calculation. This may be a real difference between surface bursts and free-air bursts due to energy losses from drag at the shock wave-ground interface. However, it should be pointed out that Porzel (ref. 19) has developed a free-air shock propagation theory that disagrees with the present calculations and agrees very well with the surface burst data.

6. CONCLUSIONS

Hydrocode calculations have been carried out to 0.2 psi and extended to 0.00016 psi for a nuclear explosion in real air and for a TNT explosion in real air. The resulting pressures agree well with data near 0.001 psi from high altitude explosions of pentolite spheres.

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Table I

Peak Overpressure Vs Radius

Overpressure (psi)	Overpressure (bars)	Ideal Nuclear Radius (km)	Real Nuclear Radius (km)	1-lb TNT Radius (m)
25600.	1765.	0.01548		
21660.	1493.	.01637		
18470.	1274.	.01726		
14420.	994.4	.01875		
11470.	791.2	.02024		
9281.	639.9	0.02172	0.0192	
7616.	525.1	.02321	.0204	0.042
6326.	436.2	.02469	.0215	.054
5313.	366.3	.02618	.0227	.067
4506.	310.7	.02766	.0240	.082
3854.	265.8	0.02915	0.0252	0.097
3138.	216.4	.03123	.0268	.120
2394.	165.0	.03420	.0292	.154
1868.	128.8	.03718	.0314	.185
1487.	102.5	.04015	.0339	.219
1204.	83.00	0.04312	0.0362	0.250
989.3	68.21	.04609	.0385	.285
823.3	56.77	.04907	.0410	.318
692.9	47.77	.05204	.0435	.350
589.1	40.62	.05501	.0460	.380
505.3	34.84	0.05798	0.0485	0.412
413.4	28.50	.06214	.0520	.458
317.8	21.91	.06809	.0575	.519
250.4	17.26	.07404	.0624	.580
201.5	13.89	.07999	.0687	.642
165.1	11.39	0.08594	0.0740	0.700
137.5	9.481	.09189	.0789	.760
116.1	8.006	.09784	.0846	.810
99.27	6.844	.1038	.0892	.875
85.79	5.915	.1097	.0946	.910
74.87	5.162	0.1157	0.0997	0.955
62.78	4.329	.1240	.1069	1.02
50.08	3.453	.1359	.1182	1.14
40.97	2.825	.1479	.1295	1.25
34.22	2.359	.1598	.1404	1.35
29.09	2.006	0.1717	0.1516	1.45
21.93	1.512	.1956	.173	1.65
19.38	1.336	.2075	.184	1.75
17.28	1.191	.2194	.194	1.84
13.56	0.9347	.2481	.221	2.08

Table I (Cont'd)

Overpressure (psi)	Overpressure (bars)	Ideal Nuclear Radius (km)	Real Nuclear Radius (km)	1-lb TNT Radius (m)
11.38	0.7847	0.2719	0.243	2.27
9.743	.6718	.2958	.265	2.45
8.474	.5843	.3196	.284	2.63
7.468	.5149	.3435	.307	2.82
6.654	.4588	.3673	.329	3.00
5.426	0.3741	0.4150	0.370	3.39
4.549	.3137	.4627	.413	3.77
4.074	.2809	.4960	.442	4.01
3.533	.2436	.5436	.489	4.40
3.109	.2144	.5912	.520	4.76
2.769	0.1909	0.6389	0.562	5.15
2.491	.1717	.6865	.603	5.50
2.065	.1424	.7818	.695	6.30
1.899	.1309	.8294	.731	6.67
1.586	.1093	.9437	.836	7.60
1.390	0.09585	1.039	0.922	8.4
1.235	.08518	1.134	1.01	9.1
1.110	.07655	1.228	1.09	9.8
1.007	.06942	1.323	1.18	10.7
0.9202	.06345	1.417	1.265	11.4
0.8466	0.05837	1.510	1.35	12.18
.7283	.05022	1.697	1.52	13.66
.6377	.04397	1.884	1.68	15.08
.5662	.03904	2.070	1.85	16.66
.4609	.03178	2.441	2.18	19.60
0.3873	0.02670	2.811	2.51	22.54
.2917	.02011	3.549	3.17	28.37
.2326	.01604	4.286	3.82	34.09
.1927	.01329	5.022	*4.48	39.76
.1641	.01131	5.757	*5.14	*45.9
0.1426	0.009830	6.492	*5.79	*51.8
.1125	.007757	7.960	*7.10	*63.5
.09258	.006383	9.427	*8.41	*75.2
.07845	.005409	10.89	*9.71	*86.9
.06793	.004683	12.36	*11.03	*98.6

* Scaled from the ideal nuclear data.

Table I (Cont'd)

Overpressure (psi)	Overpressure (bars)	Ideal Nuclear Radius (km)	Real Nuclear Radius (km)	1-lb TNT Radius (m)
0.05981	0.004124	13.82	*12.33	*110.3
.04813	.003318	16.75	*14.94	*133.7
.04015	.002769	19.68	*17.55	*157.0
.03438	.002370	22.61	*20.2	*180.
.03001	.002069	25.54	*22.8	*204.
0.02659	0.001834	28.47	*25.4	*227.
.02318	.001598	32.13	*28.7	*256.
.01846	.001272	40.91	*36.5	*326.
.01526	.001052	46.76	*41.7	*373.
.01076	.0007416	64.32	*57.4	*513.
0.007659	0.0005281	87.73	*78.2	*700.
.004813	.0003318	134.5	*120.	*1073.
.002880	.0001986	216.5	*193.	*1728.
.001684	.0001161	356.9	*318.	*2850.
.0007337	.00005058	778.2	*694.	*6210.
0.0001639	0.00001130	3212.	*2865.	*25600.

* Scaled from the ideal nuclear data.

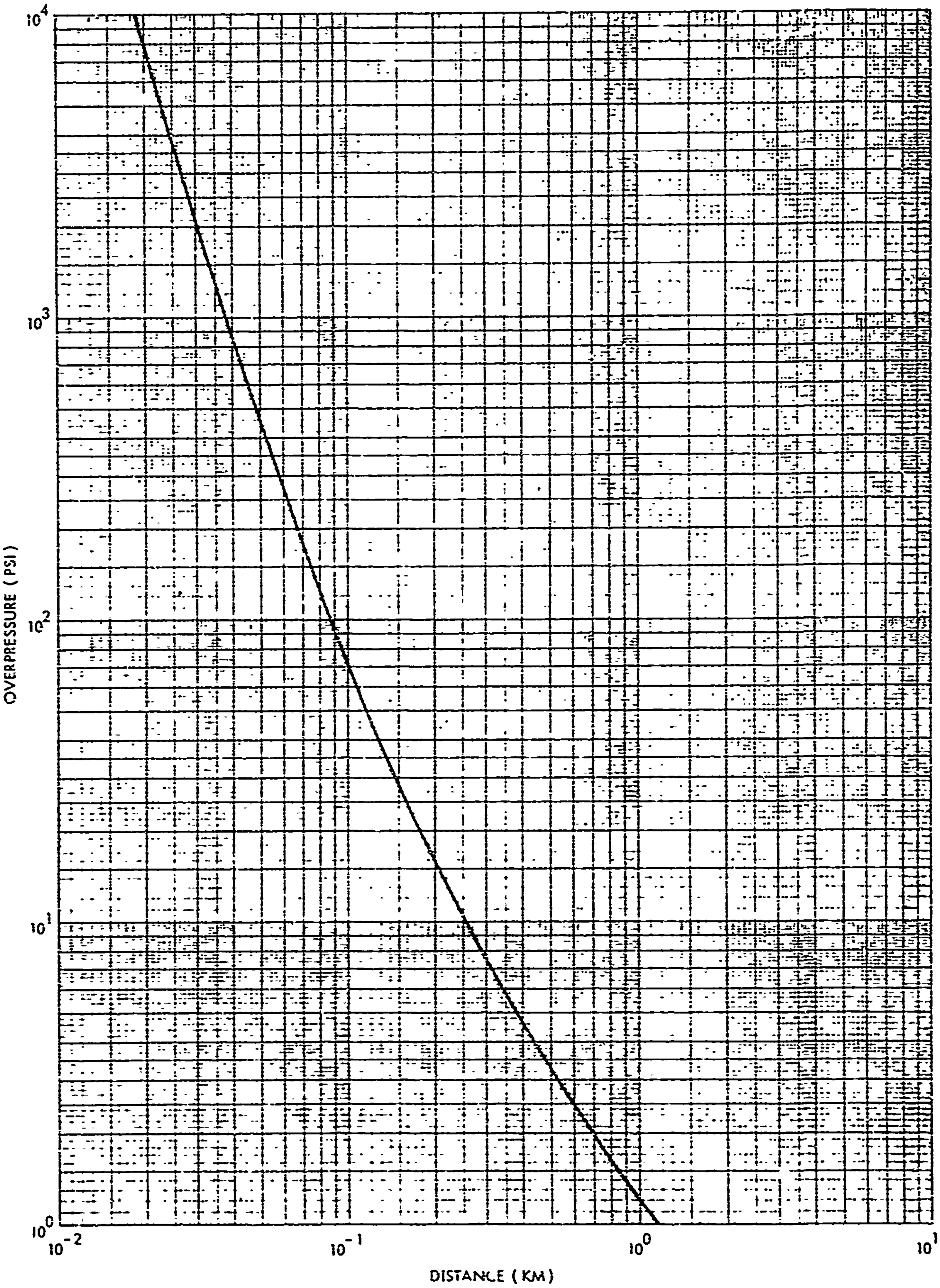

FIG. 1 PEAK OVERPRESSURE VS DISTANCE FOR 1 KT NUCLEAR EXPLOSION IN SEA-LEVEL REAL AIR
SHEET 1

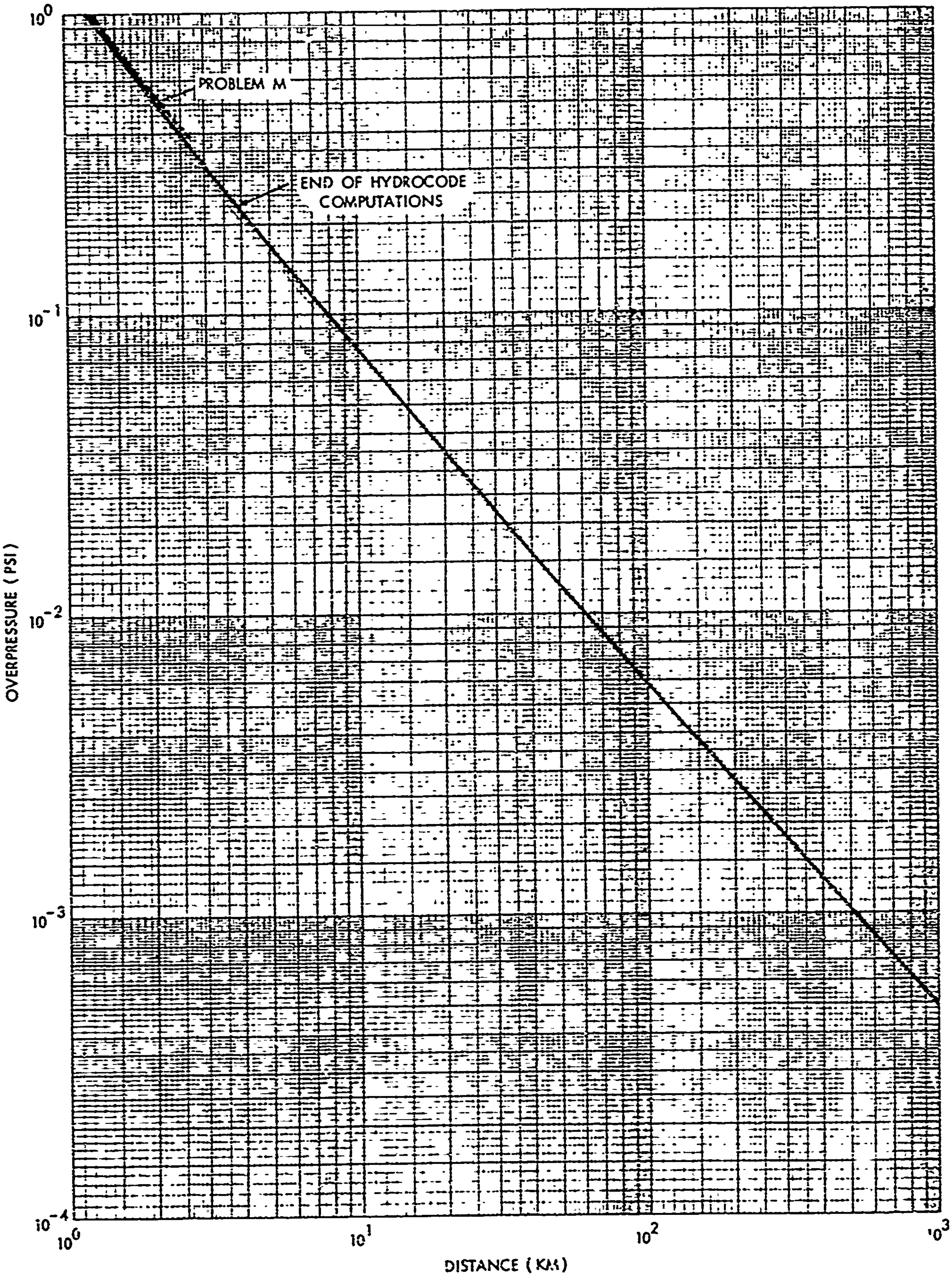

FIG. 1 (CONTINUED) SHEET 2

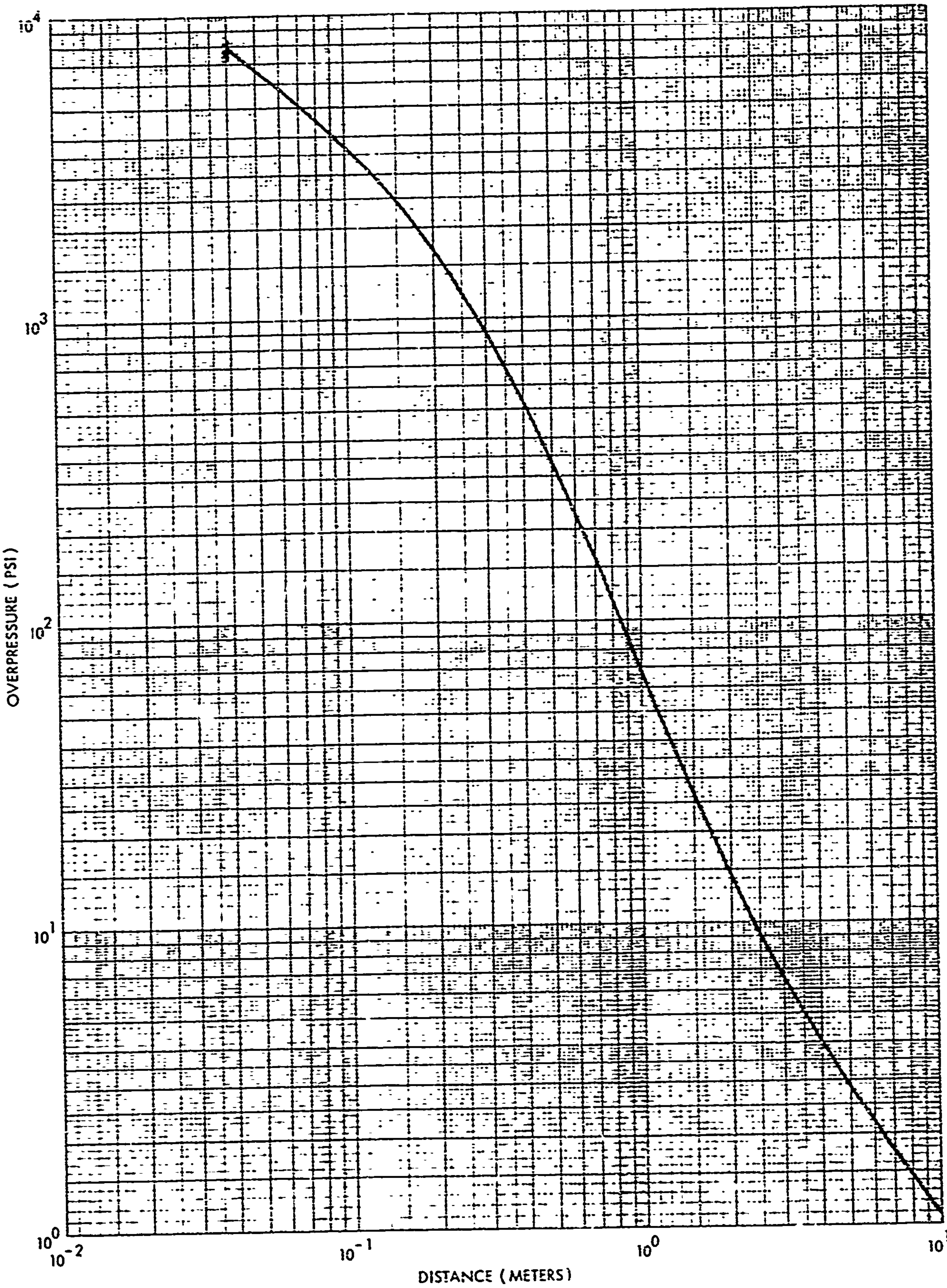

FIG. 2 PEAK OVERPRESSURE VS DISTANCE FOR 1-LB TNT AT SEA LEVEL
SHEET 1

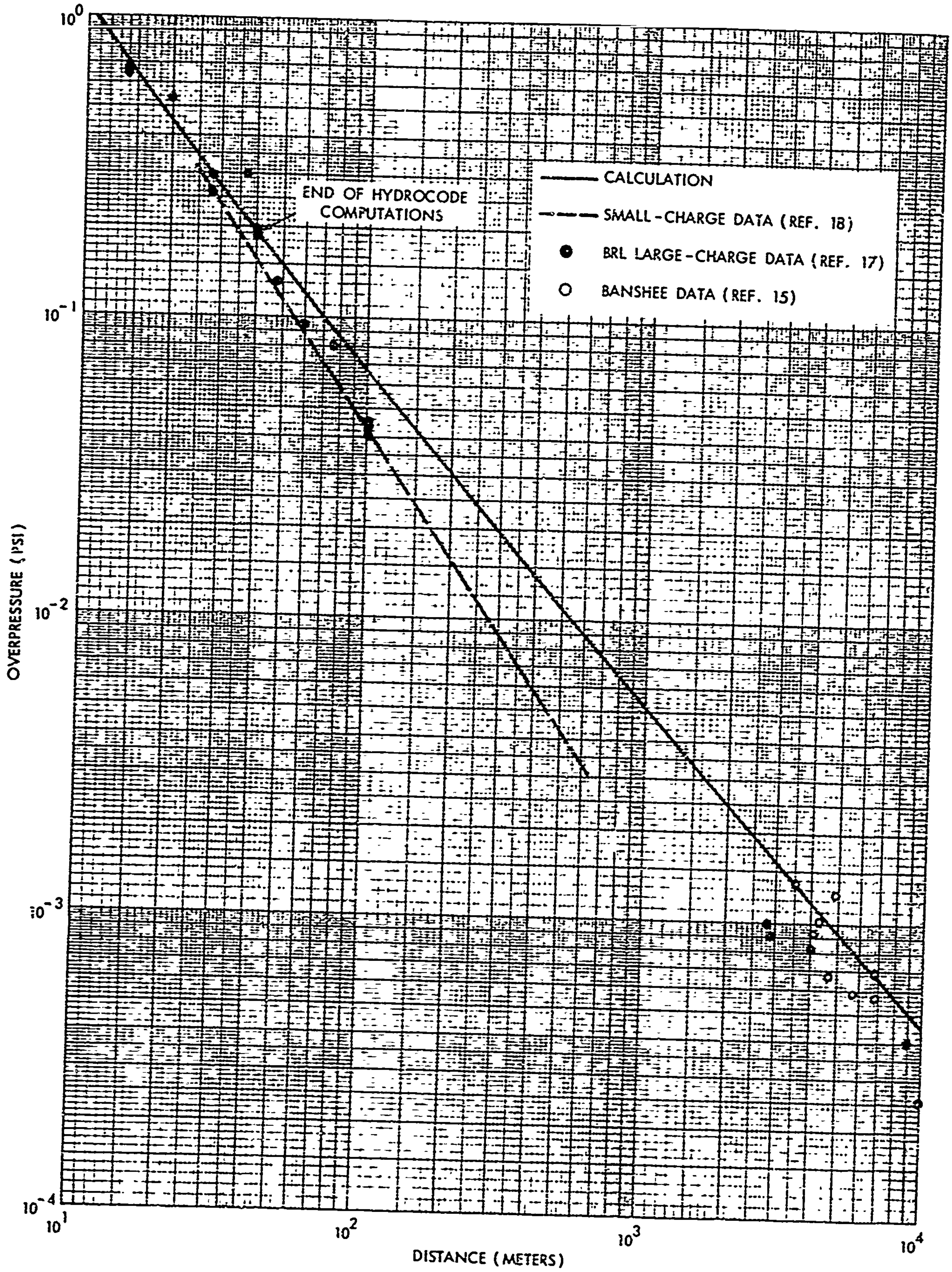

FIG. 2 (CONTINUED) SHEET 2

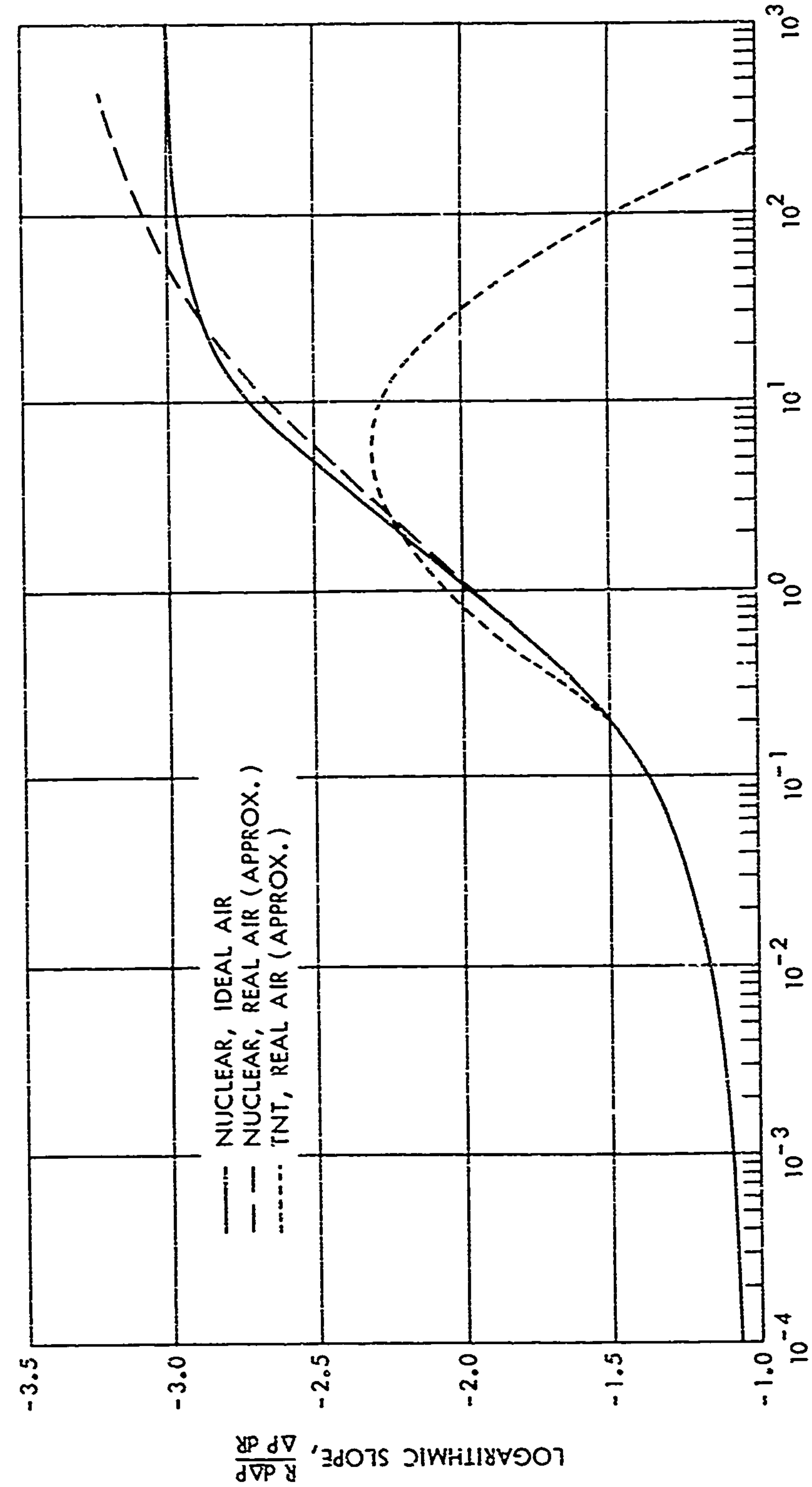

FIG. 3 LOGARITHMIC SLOPE OF OVERPRESSURE VS. DISTANCE CURVES

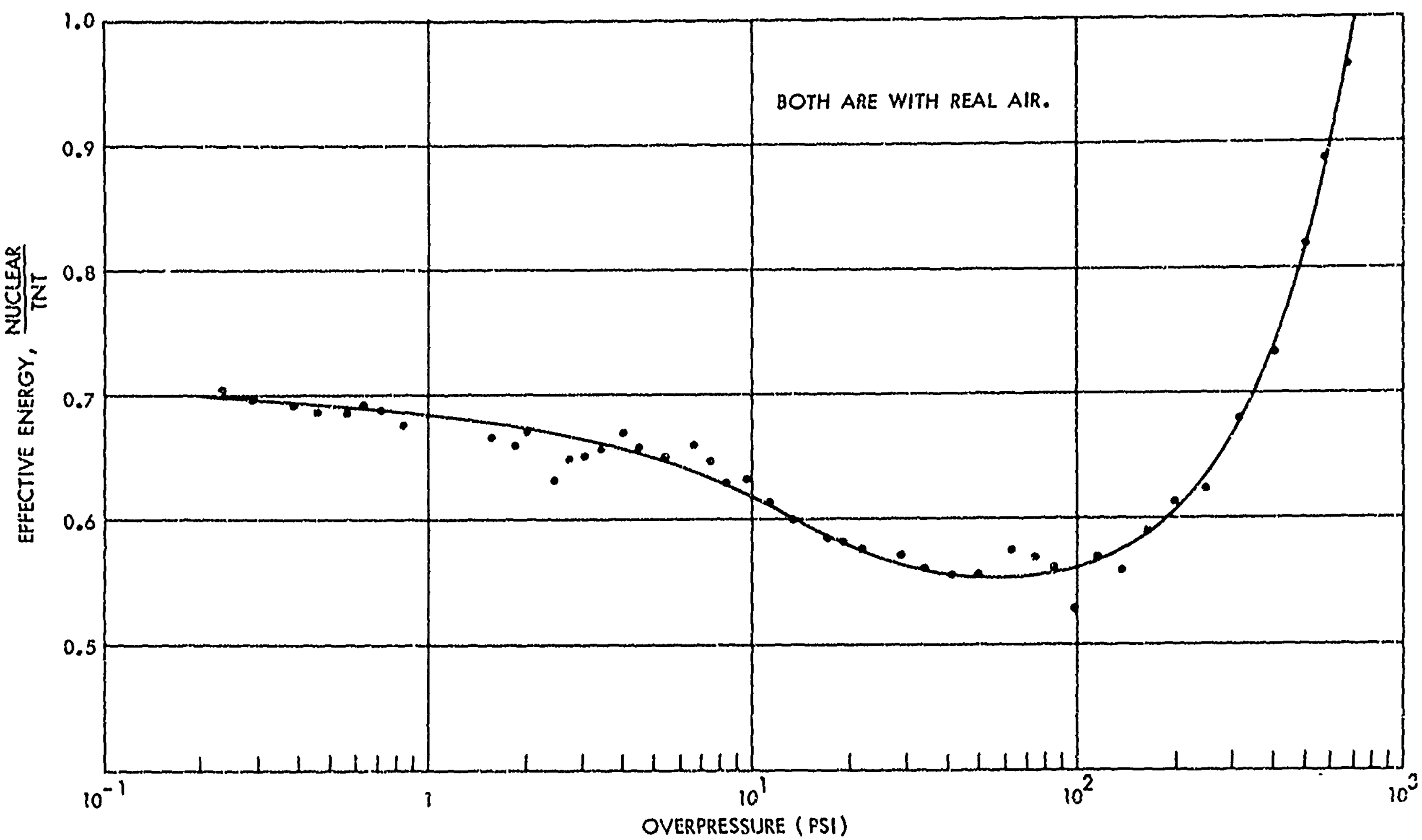

FIG. 4 EFFECTIVE BLAST YIELD OF NUCLEAR RELATIVE TO TNT

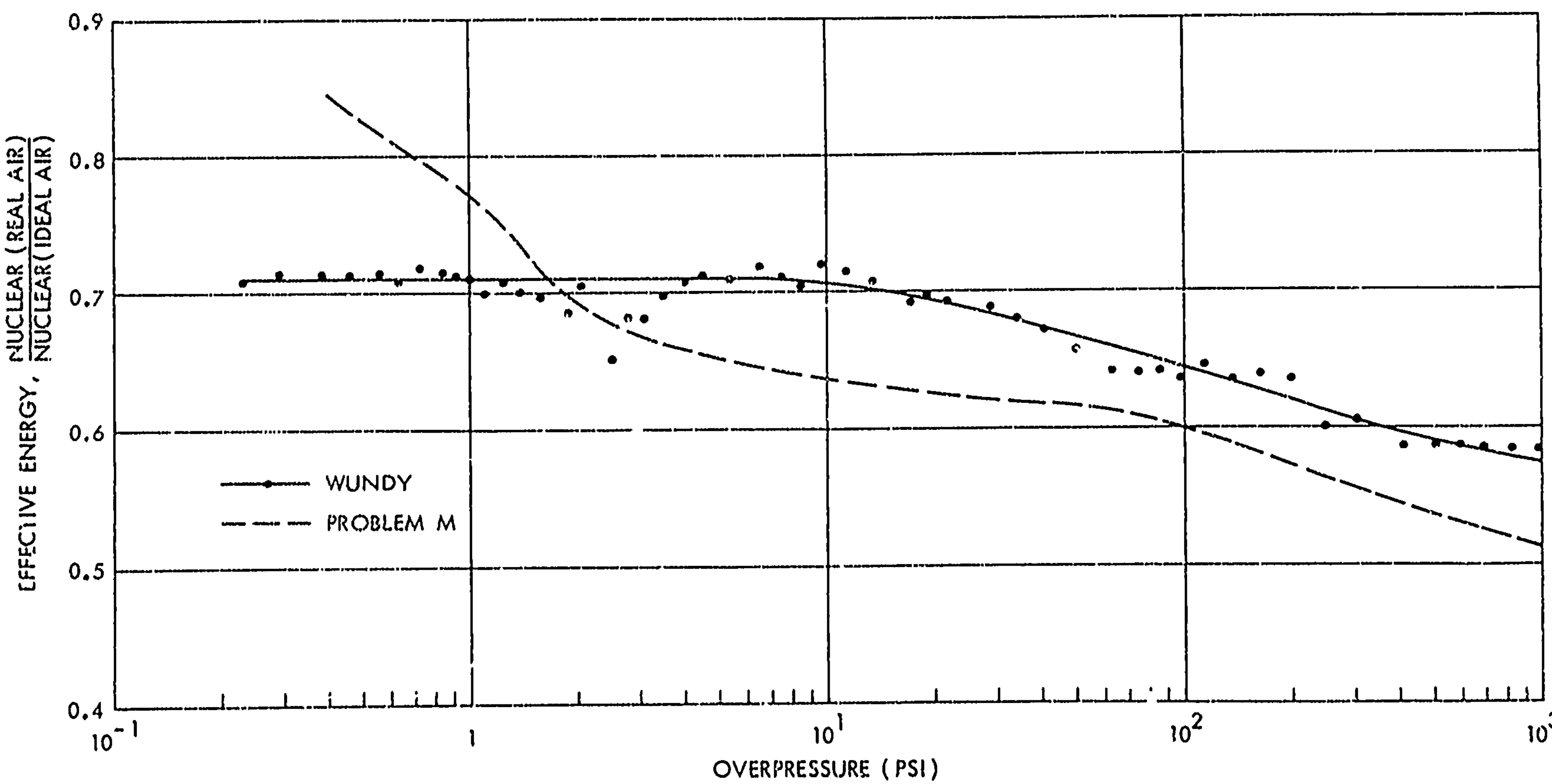

FIG. 5 EFFECTIVE BLAST YIELD OF NUCLEAR EXPLOSION IN REAL AIR RELATIVE TO IDEAL AIR

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13 ABSTRACT

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